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A REPORT ON THE POSSIBLE BENEFITS OF USING HIGH-TEMPERATURE SUPERCONDUCTOR MATERIALS IN PARTICLE ACCELERATOR DESIGN

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A REPORT ON THE POSSIBLE BENEFITS OF USING HIGH-TEMPERATURE SUPERCONDUCTOR MATERIALS IN PARTICLE ACCELERATOR DESIGN

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ABSTRACT

This report discusses different design concepts for particle beam accelerators. It demonstrates that, with the use of high-temperature superconducting materials, a more compact, lighter, and more robust accelerator design can be realized for the space-based neutral particle beam (NPB) accelerator.

ACKNOWLEDGEMENTS

PREFACE

This report explores the possibility that new high-temperature superconducting materials may be incorporated in linacs in Neutral Partical Beam Weapons. If this approach proves feasible, smaller and lighter power modules for use in the space environment may become possible, thereby advancing the goals of the SDIO.

This report has not been subjected to formal review.

CONTENTS

I. INTRODUCTION

In the winter of 1987, a compound of yttrium, barium, and copper oxides was shown to have a superconducting transition at about 94 K. This news was received with great excitement in the scientific community, because it was an indication that instruments and systems incorporating superconducting materials could now be designed to operate at liquid nitrogen temperatures rather than at the more difficult and costly liquid helium temperatures.

This report explores the role that the new high critical temperature (T_c) superconductors might play in the design of the accelerator to be used in generating a neutral particle beam for the SDI mission. First, a brief history of the linear accelerator (linac) is presented, followed by a picture of the type of design that current thinking in the NPB community would probably produce. The report then speculates on the nature of the linac that innovative thinking would produce if the ideal high T_c materials were available.

II. HISTORY OF CONVENTIONAL LINEAR
ACCELERATORS

The first linear accelerator for heavy positive ions was developed by Wideroe in 1929. This forerunner of all resonance accelerators consisted of an ion source and two cylindrical electrodes, all co-axial. An alternating voltage was applied between the two electrodes with the frequency so adjusted that the accelerating potential reversed polarity just as the particles bridged the gap between ion source and first electrode. Just as the ions completed their drift through the first electrode, the polarity again reversed, thereby producing a second accelerating gap. The result was that twice as much energy was produced as could be produced by a single accelerating electrode. E.O. Lawrence, D.H. Sloan, and W.M. Coates extended the concept (as shown in Fig. 1) to include more than ten electrodes in the final accelerator.
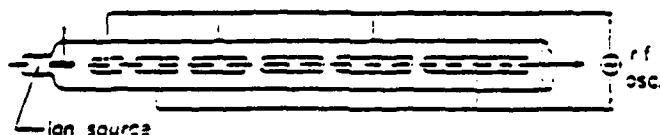
Figure 1. Early Lawrence-Sloan Accelerator

Successive electrodes were alternately connected to the two bus bars between which RF voltage was applied. The techniques of the 1930's only permitted the acceleration of light ions to energies of no more than 2 MeV. The velocity of the particles increases between successive electrodes. The accelerator is characterized by having an intergap spacing of 1/2 v/f (or 1/2 $\beta\lambda$), where v is the particle's speed, f is the radio frequency, λ is the wavelength, and β is the particle's speed expressed as a fraction of the speed of light. In these early accelerators, the phase of the applied voltage was kept close to 90° so that the energy gained in each gap was the maximum. After World War II, new techniques

involving UHF radar, pulsed power supplies, and waveguide propagation were applied to the evolving technology of accelerators. With the older designs, the low frequencies used (1 to 10 MHz) led to intolerably long drift tubes as designers sought to achieve higher energies. With new high-frequency power sources, shorter drift tubes could be used. However, at radio frequencies, the gaps conduct large displacement currents which, in turn, draw a large current from the RF generator, and adjacent drift tubes act as radiating dipoles. L. Alvarez and others solved the HF (high frequency) problems by enclosing the accelerating gaps in cavities having the resonant frequency of the driver. The evolution of this type of accelerator is depicted in Fig. 2. In (a), the distance between cavities is varied; in (b), the cavity length is varied. In both arrays, $\beta\lambda$ is the gap separation. These arrays all use the TM_{010} mode[1] of standing wave. Figure 2(c) shows the Alvarez design with the internal cavity walls removed and Fig. 2(d) shows a cutaway drawing of a drift tube linac. Figure 3 depicts the electric field lines and wall currents in two cavities of two different types of array. The one in (a), is of the type shown in Fig. 2. Note that the currents in the common wall are essentially equal and therefore cancel. The removal of the wall will therefore not affect the field pattern; and its removal leads to the Alvarez linac of Fig. 2c. In recent years, this basic accelerator has been improved by installing magnetic quadrupole lenses inside the drift tubes for beam-focusing and a Radio Frequency Quadrupole preaccelerator to improve injection energy. An important advantage of the early Alvarez design is that a single power supply can feed many cavities. The Alvarez drift tube linac forms the basis of current thinking for a linac of 200 to 300 MeV ions for the Neutral Particle Beam (NPB) Weapons program.[2] Linacs of this type generally have gradients of the order of 1 to 2 MeV/m. Even with 3 MV/m, a 250 MeV linac would be on the order of 75 m long.

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[1] See, for example, J.D. Jackson, *Classical Electrodynamics*, Second Edition, Chapter 8, John Wiley & Sons, Inc. (1975).

[2] Various reports, SDIO Library.
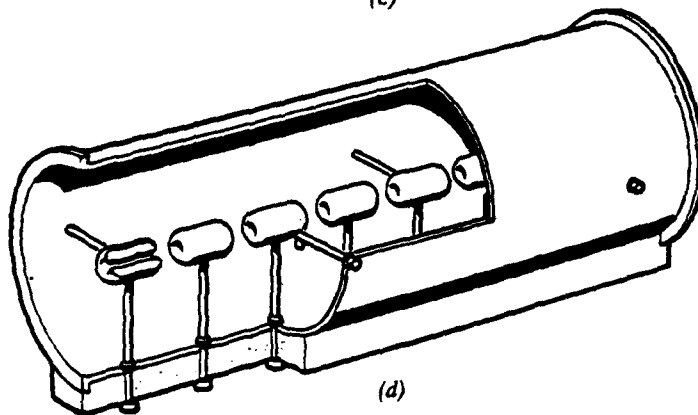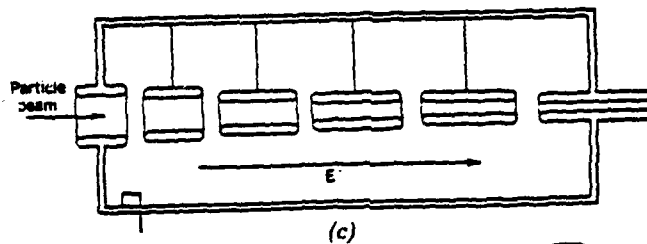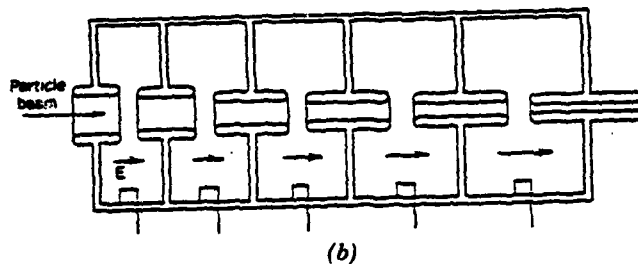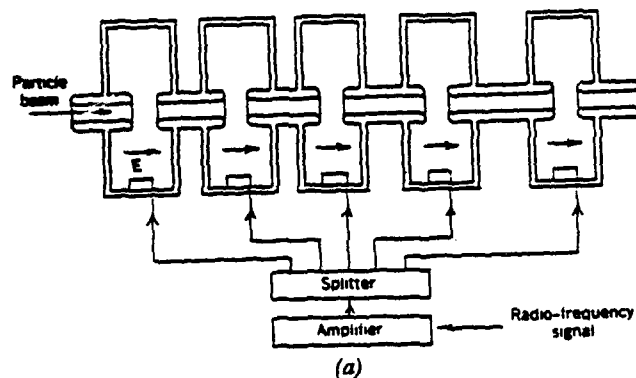
Figure 2. Evolution of drift tube linear accelerator. (a) Array of resonant cavities in the $\beta\lambda$ configuration with particle synchronization maintained by variation of distance between cavities. (b) Simplified $\beta\lambda$ structure with synchronization by varying cavity length: uniform resonant frequency maintained by variation of drift tube and acceleration gap geometry. (c) Alvarez linac tank. (d) Cutaway drawing of drift tube linac with couplers to shift frequency of undesired modes.

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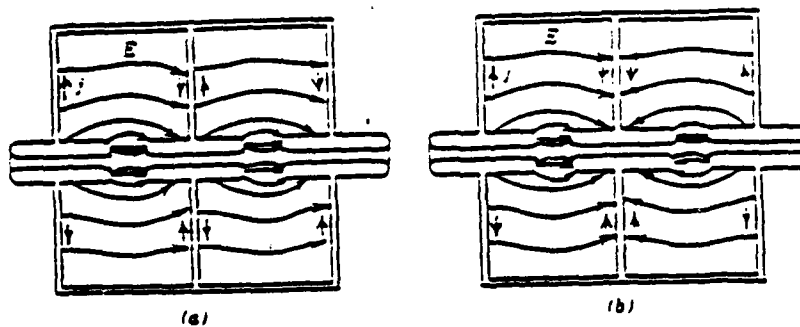
Figure 3. Electric field lines and wall currents of TM_{010} modes in two cavities of standing wave linear accelerator: (a) $\beta\lambda$ linac, (b) 1/2 $\beta\lambda$ linac

III. SUPERCONDUCTING LINACS

To understand the importance of cooling in the design of a linear accelerator, it must be understood that, in a conventional linac, about half the power goes into the particle beam and half is lost in heating the walls. The power per unit length that is dissipated in the walls is given by the expression $E_L{}^2/R_{SL}$,[3] where E_L is the voltage per unit length and R_{SL} is the shunt resistance per unit length. A gradient of about 2 MV/m in a water-cooled copper accelerator corresponds to a power dissipation on the order of 50 kW/m.[4] With superconducting walls, the shunt resistance becomes very great; and, depending upon the frequency, the power dissipated in the walls is reduced to the order of tens of watts per meter. In electron accelerators, where the speed of the electrons is close to the speed of light ($\beta = 1$), the section spacings are equal and the electric field is uniform along the entire length of the accelerator. For protons, the long drift tubes force a smaller fraction of the accelerator length to sustain the high fields for a given total length. In a superconducting electron linac, one can achieve gradients of the order of 10 MV/m. At about 10 MV/m, thermal loading of the superconductor, i.e., thermal conductivity at the operating frequency, becomes a problem. Beyond this point, other problems arise, mainly multipactoring[5] and field emission. Some workers assume that, for protons, despite the higher fields, the larger cavities and lower frequencies will enable field gradients of 10 MV/m. A 250 MeV accelerator would then be 25 m long instead of 75 m.

In addition to using superconductivity, accelerator specialists, e.g., Pierre Grand of Brookhaven National Laboratory (BNL), have suggested returning to the design of Lawrence and Sloan, with some modifications. This design is impractical without superconductivity because of high power dissipation, but with superconductive cavities, the design becomes competitive in terms of power consumption and provides other

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[3] See, for example, Stanley Humphries, Jr., *Principles of Charged Particle Acceleration*, John Wiley & Sons, Inc. (1986).

[4] Private communication from Samuel Penner.

[5] The resonant growth of electron current from multiple impacts of electrons on the walls of the cavity. See S. Humphries cited above.

important benefits. The schematic is shown in Fig. 4. The decoupled individual cells are all the same size. Instead of waiting for drift tubes to restore the desired phase, phase shifting modules between successive cells permit a particle which has just crossed one cell to arrive in the next at just the correct phase for optimum acceleration. This structure is also more rugged than the Alvarez type and therefore more amenable to being lifted into a space environment. The design provides additional robustness by virtue of the use of identical cells, i.e., the loss of an individual cell can be compensated for.
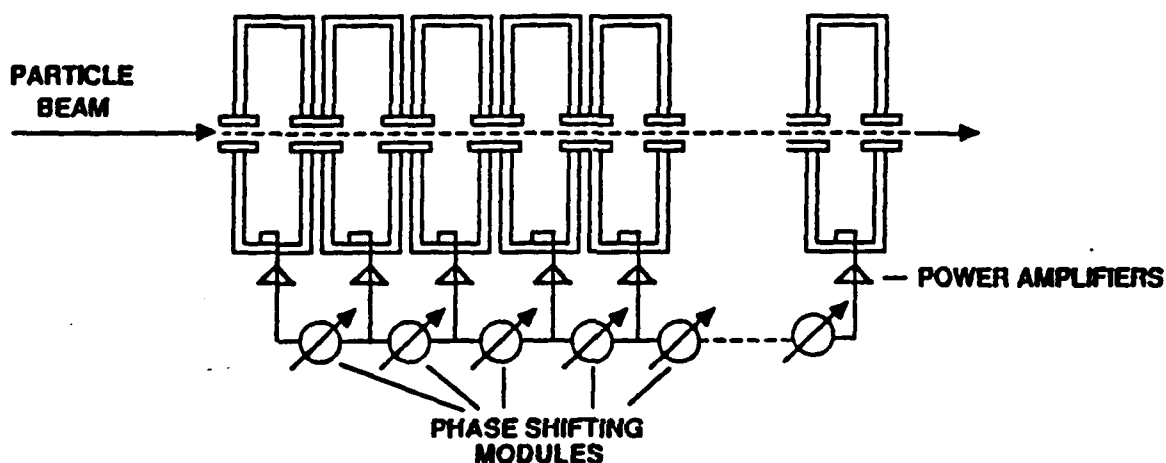
Figure 4. A Recent Modification of the Lawrence-Sloan Type of Accelerator

Superconductivity permits a higher field gradient which leads to a significantly shorter and lighter accelerator and reduces the power requirement for the accelerator *itself*. These advantages all accrue from the exploitation of conventional niobium technology. What additional advantages can be achieved by going to the new high T_c superconductors? There are principally two, and they are important. The first is that the accelerator will be robust against large temperature excursions.[6] The second is improved cryogenics economy. At the temperature of liquid hydrogen, 20 K, and employing a Stirling cycle refrigeration system, it takes about 1700 W of refrigeration to achieve 1 W of cooling.

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[6] This condition obtains because the operating temperature is generally selected to be at one-half to three-quarters of the critical temperature. Therefore, the higher the critical temperature, the greater the temperature swing that can be tolerated without losing superconductivity.

At a temperature of liquid nitrogen, 77 K, it takes only about 370 W.[7] [A discussion of cryogenic operating conditions and required power at various temperatures is given in Appendix A.] The use of these materials thus appears to have great potential merit. Accelerator characteristics for a baseline cold copper cavity (20 K) accelerator and a new model of the Sloan-Lawrence type of accelerator with high T_c superconductor cavity are compared in Table 1.

Table 1. NPB Accelerator Characteristics for a 250 MeV, 100 MA System[†]

Characteristics	Baseline model not superconducting	Baseline (20K) cold copper cavity not superconducting	New model (Sloan-Lawrence) with high T_c superconducting components
Accelerator power requirements	*	35 MW (80% efficient)	30 MW
Length	*	25 m	8 m
Weight		30,000 + lbs	10,000
Robustness	*	Single RF power supply	Multiple RF power supplies (compensation)
Tunable for different masses	*	Designed for one mass particle only	Mass compensation
Cryogenics	*	Liquid hydrogen or helium	Depends on T_c

* Information presented in classified briefing.

† Information obtained from various NPB reports.

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[7] These power levels are given for cooling from room temperature to the temperature of the coolant. In space, where the ambient temperature may be of the order of 100 K, cooling economies are even better.

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IV. CONCLUSIONS AND RECOMMENDATIONS

There are several benefits to be gained from using high-temperature superconducting materials in NPB accelerator designs for SDI applications. If such materials are incorporated into the conventional Alvarez design, a reduction in power requirements and cooling costs would be expected (see Table 1), along with improved operating performance due to better control of surface phenomena (reduced multipactoring and field emissions) as well as a reduction in the effect of temperature fluctuations.

Also, with the use of high T_c superconductors,[8] the Sloan-Lawrence concept with the phase-shifting modules, as shown in Fig. 4, becomes economically competitive. In addition to the benefits already mentioned, this design would provide other benefits such as robustness resulting from the use of individual power supplies to feed the cavities. If one power supply is damaged, the accelerator does not shut down. Power supplies in the other cavities would be adjusted to meet the phasing requirement, and the accelerator would still function, although at a somewhat lower particle energy. Use of identical cavities would also simplify production and electronic tuning, and facilitate replacement of cavities in space.

This design offers additional flexibility because different mass particles could be accelerated by a simple electronic adjustment of the power supply phases. The same accelerator could thus serve several functions in the SDI system. A major benefit in deployment and operation would be gained from the anticipated size and weight reduction shown in Table 1.

The benefits described above are summarized in Table 2. To utilize the high T_c superconductors in the NPB accelerator design, much materials research and development work will have to be performed. Since there are many proposed applications for the high T_c materials, ranging from microelectronic circuitry to electromagnetic motors for

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8   Low T_c superconductors will work, but higher cryogenic costs and the loss of robustness due to moderate temperature swings will defeat our purpose.

ships, much of the required developmental work will be undertaken by other sponsors to promote their favorite applications. The production of wires for power transport or superconducting magnets, for example, is expected to be on many research agendas. Some research areas that specifically address the accelerator design problem should be funded by the SDIO; otherwise, results may not be forthcoming in the near future. The materials issues that specifically relate to accelerator design are listed below.

Table 2. Benefits of Using High T_c Superconductor Materials in NPB Designs

Benefit	Sloan-Lawrence Design	Alvarez Design
1. Lower power requirements	X	X
2. Lower cooling costs	X	X
3. Robustness		
Individual RF power supplies to cavities		X
Better control of surface phenomena (multipactoring and field emission	X	X
Easier cavity replacement		X
Mechanical structure strength		X
4. Flexibility		
Reduced effect of temperature fluctuations	X	X
Particle mass variability		X
5. Identical cavities		
Simplified production		X
Electronic tuning		X
6. Lower weight and smaller size	X	X

- Research dealing with high T_c superconducting material properties at GHz frequencies
    - Specific heat, thermal conductivity
    - Electrical resistivity
    - Anisotropy effects
    - Radiation effects
    - Oxygen stoichiometry
- Materials Processing Issues
    - Surface preparation technology
    - Fabrication of cavities
    - Wire fabrication for magnets

In the case of materials properties, the emphasis should be on research at GHz frequencies; because, as shown in Appendix B, the materials properties vary drastically in the GHz region where the accelerator cavities would be operating.

APPENDIX A

SUPERCONDUCTOR COOLING POWER REQUIREMENTS

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SUPERCONDUCTOR COOLING POWER REQUIREMENTS

An assessment of the overall economics of using cryogenics in the architecture of an accelerator system must balance the gains achieved against the cost of the new technology. The gains include the reduced size and weight of the system and the consequent greater ease and reduced cost of putting the system into orbit. Size and weight reduction would be the result of improved conductivity of cavity walls and the higher electric field gradients. These improvements give rise to shorter and lighter accelerator tubes with a reduced power demand and, therefore, smaller and lighter power modules. The costs will depend upon research and development work in obtaining superconducting materials and in fabricating the resonant cavities using these materials.

Fabrication of microwave cavities for accelerators made of the new superconducting materials will not be undertaken for ground installations. Development costs required to learn the art of fabrication to support MeV/m per fields for these new materials could hardly be justified unless a significant saving in both the volume needs and cooling capacity of spaceborne systems is implied.

In considering the implications for the cryogenic plant, a useful parameter is the input power (watts) required to produce a given cooling capacity at the specified temperature. A figure of merit commonly used is the watts of input power to the cooling plant per watt of energy removed at the lower temperature. The realization of any system is limited on one hand by the theoretical thermodynamic maximum efficiency and on the other by the techniques which are specific to the cooling system used. The theoretical efficiency of a refrigerator depends on the temperature difference between the reservoir (usually room temperature) and the operating temperature of the working element. A representative state-of-the-art variation of the watts per watt as a function of temperature is given below.[*]

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[*] The numbers are taken from tabulated values of production refrigerators, *The Infrared Handbook*, W.L. Wolfe and G.J. Zissis, eds.; Environmental Research Institute of Michigan, 1985, Table 15-12.

Temperature	Watts/Watt
17 K	1735
77 K	368

A significant reduction in required power is possible if the operating temperature can be increased from 20 K to 90 K.

In a spaceborne system, energy is removed from the system by radiation and any reduction in the power that must be dissipated is reflected in the area of the radiators.

Cooling power required for a normal linac is about 50 kW/m, while for a superconducting linac this requirement would drop to less than 14 W/m.* To cool at 14 W/m, it will be necessary to use new, but as yet unproven materials, and the properties of these materials at high frequencies (0.5 to 3 GHz) must be determined. Again, the driving forces are cryogenic costs and robustness.

The latent heat of vaporization at the boiling points of several cryogenic materials is presented in Table A-1.

Table A-1. Heats of Vaporization at the Boiling Points of Cryogenic Materials

Coolant	Temperature (K)	Density ρ (g/cm^3)	Latent Heat of Vaporization L_V(J/g)	Latent Heat of Vaporization L_V(J/cm^3)
Helium	4.2	0.12	20	2.4
Hydrogen	20	0.07	448	31.0
Nitrogen	77	0.80	199	159.0
Argon	87	1.3	162	210.0

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* Scaling from values given in K.W. Shepard, G.P. Zinkam, *IEEE Trans. Nucl. Sci.*, Vol. *NS-30* (No. 4), 3339, August 1983.
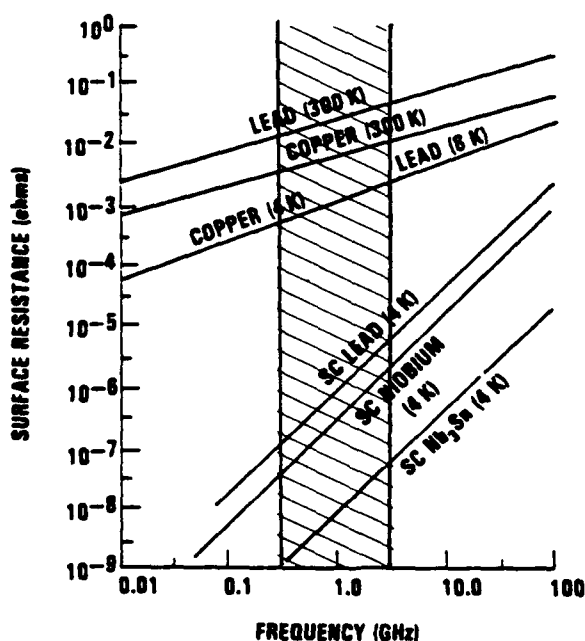
APPENDIX B

FREQUENCY DEPENDENCIES OF SUPERCONDUCTING MATERIAL PROPERTIES

APPENDIX B
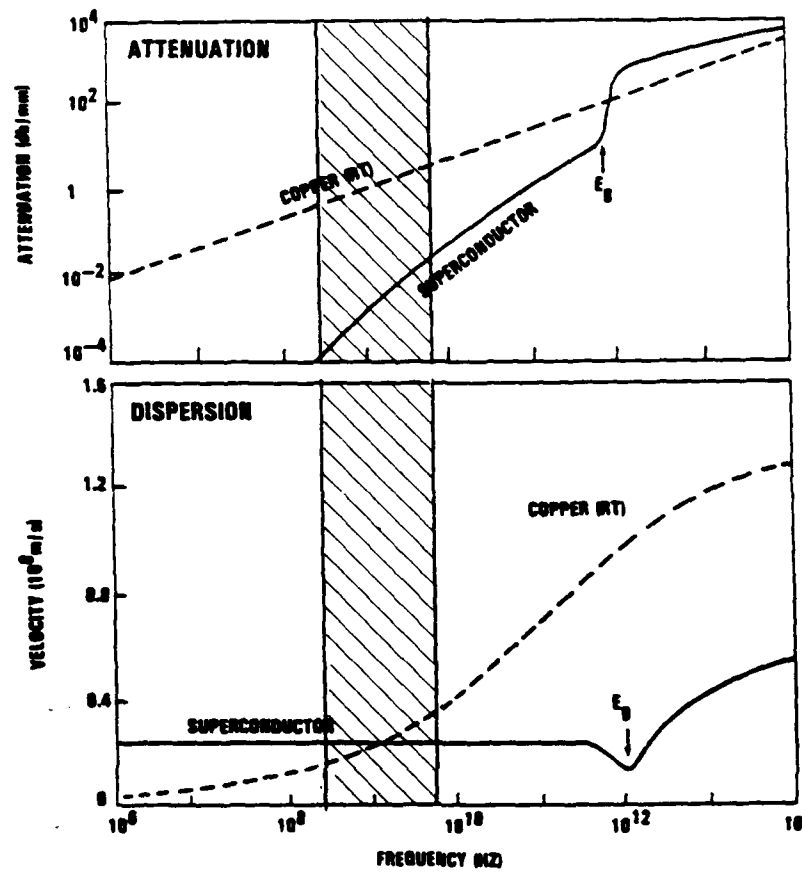# FREQUENCY DEPENDENCIES OF SUPERCONDUCTING
MATERIAL PROPERTIES

The information presented in Figs. B-1 and B-2 is adopted from *Naval Research Reviews*, Vol. *37*, 1, 1985. Fig. B-1 depicts the surface electrical resistance which is of interest in accelerator cavity applications and Fig. B-2 the attenuation and dispersion properties of interest to transmission line application.

Source: Based on figure appearing in *Naval Research Reviews*, Vol. *37*, 1985

Figure B-1.   Frequency Dependencies of Superconducting Material Properties, NPB Application

Source: Based on figure appearing in *Naval Research Reviews*, Vol. *37*, 1985

**Figure B-2.   Frequency Dependencies of Superconducting Material Properties,
Transmission Line Application**